THE CANADIAN PROGRAMME OF EXPERIMENTAL MEASUREMENT OF SEA-STATE CHARACTERISTICS BY SKY-WAVE RADAR

by

E.L.Winacott
Communications Research Centre, Department of Communications,
C.R.C. PO Box 11490, Station H, Ottawa Ontario, Canada K2H 8S5

C.Roche
Centre for Cold-Ocean Resources Engineering, St. John's, Newfoundland, Canada

J.Y.K.Chan
Miller Communications Systems, Ottawa, Canada

SUMMARY

In June, 1980, a limited programme of sky-wave radar measurements was undertaken to investigate the feasibility of measuring sea-state characteristics off the coast of Newfoundland. The programme involved the collection of data by the Communications Research Centre's (CRC) Sampled Aperture Receiving Array (SARA) facility at Ottawa, the compilation of ground-truth maps of wave height, wind velocity and ice coverage by the Centre for Cold-Ocean Resources Engineering (C-CORE) in Newfoundland, and data analysis and interpretation by both agencies. Transmissions were provided, as part of a co-operative programme which involved other projects, by the Rome Air Development Centre transmitter facility at Ava, New York.

A number of day-time experimental runs were made between October, 1980, and April, 1982. Because it was felt that ionospheric disturbances would preclude the recording of useful results, runs were made, as much as possible, only during periods of relatively quiet ionospheric conditions.

As was expected from the earlier experience of U.S. workers, maps of wind direction usually could be derived from the data, but maps of wave heights were quite sparse: less than one-quarter of the data were useful. In fact, since the acceptance criterion developed by the U.S. workers was found to reject virtually all of the Canadian data; a manual acceptance technique had to be employed. While this technique has made possible the recovery of experimental results, it would be impractical in an operational radar.

Determination of other sea-state characteristics, such as sea-wave spectra, the magnitude of the swell component, or independent measurement of wind speed, was not possible from the data collected.

Almost all of the results were obtained by means of reflections from the F2 layer, with a few returns from the F1 layer during a period of moderate ionospheric disturbance. No effort was made to utilize E-region reflections since, in general, these were not observed during the periods of operation.

A considerable fraction of the analysis procedures had to be directed towards averaging and alignment of the sea-state spectra, in an attempt to reduce the degradation caused by ionospheric Doppler offset and smear. This problem was exacerbated by the necessity for relatively long observation periods, 50 to 100 seconds, to provide adequate resolution in the sea-state spectra, in the presence of short persistence times of ionospheric propagation paths, usually only a few seconds (and possibly only fractions of seconds).

It is hoped that, when the final analysis is complete, both an analysis algorithm and an acceptance criterion will emerge which will indicate the practicability of operation of a sea-state radar in areas close to the auroral zone.

1.0 OVERVIEW OF THE EXPERIMENT

1.1 HISTORY

An exploratory programme of experimental sea-state measurements began in Canada early in 1980, involving a number of agencies:

- the Communications Research Centre (CRC) of the Department of Communications, which operated the Sampled Aperture Receiving Array (SARA) system at Ottawa;
- the Department of National Defence, which provides funding for all SARA activities;
- the Centre for Cold Ocean Resources Engineering (C-CORE), at St. John's, Newfoundland;
- the Department of Fisheries and Oceans, which sponsors various programmes at C-CORE; and
- the Rome Air Development Centre (RADC) which provided signals from their transmitting facilities at Ava, New York.

In June, 1980, a planning meeting was held in the offices of C-CORE, attended by representatives of each of the Canadian agencies and by Mr. William Sandham, from the University of Birmingham in the United Kingdom. Mr. Sandham's address served as an introduction to the field of sea-state research as well as a description of the current activities at the University of Birmingham and Appleton Laboratories [1,2,3,4]. The objective of the Canadian programme, as defined at the meeting, was to "establish, in Canada, the technology for measuring sea-state and other ocean parameters, using high-frequency skywave radar, with a view to improving the accuracy and timeliness of information used in support of the operations of the Department of National Defence and the Department of Fisheries and Oceans".

A plan of action was agreed upon, which encompassed initial trials in late 1980, development of analysis procedures and conduct of the experiment throughout 1981, and final analysis in 1982. Later, this plan was extended to allow additional observations in 1981/82, and analysis to continue into 1983. The analysis activity is still in progress.

The Department of Communications personnel set up and carried out the experiment, and converted the recordings to a data-base of calibrated, range-gated data stored on magnetic tape. C-CORE personnel set up and operated a transponder (supplied by CRC) at a site near St. John's, and compiled hindcast maps of surface-truth data for each of the observing days. Both agencies analyzed and interpreted the results, and will separately and jointly produce reports on the findings.

Assistance by the Rome Air Development Centre, to provide signal transmissions, was required because the SARA system, originally built to carry out phase-front studies in support of direction-finding research, did not have a high-power transmitting facility.

A separate, independent programme of shore-based measurements, using a Coastal Ocean Dynamics Applications Radar (CODAR), was carried out by C-CORE, funded by the Department of Fisheries and Oceans.

1.2 COVERAGE AREA

The coverage area for the experiment is illustrated in Fig. 1. The width of the area was established by the beamwidth of the transmitting antenna, approximately 65 degrees. The maximum range was limited by the signal levels that could be achieved and by the volume of data that could be handled for analysis. In early trials, returns were recorded from the Gulf of St. Lawrence, but later that area was ignored to concentrate effort on the areas adjacent to Newfoundland.

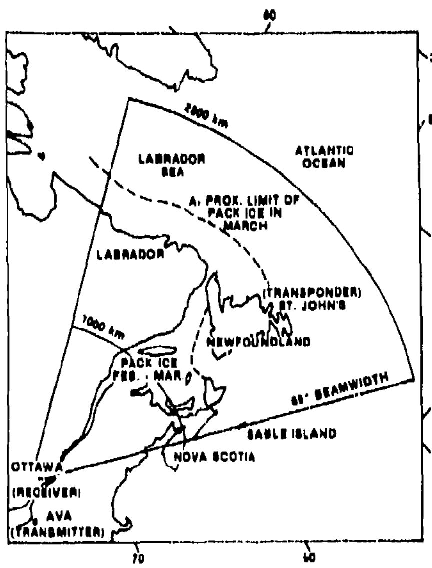

FIG. 1 Coverage Area for the Canadian Sky-Wave Sea-State Experiment

The azimuthal extent was determined by the beamwidth of the transmitting antenna.

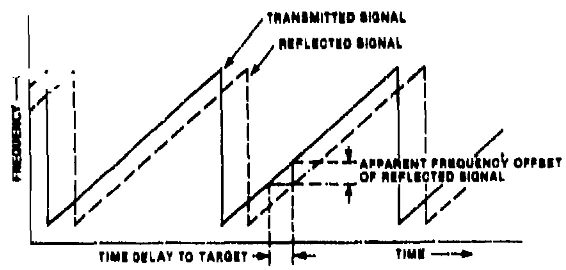

FIG. 2. Frequency-Modulated Continuous-Wave Transmissions

The reflected signal, arriving at the receiver after a propagation time delay, appears to be offset in frequency. The scales are greatly exaggerated for clarity: the extent of the frequency sweep is typically 50 KHz; the offset of the reflected signal is less than 60 Hz.

In the early trials, problems of array ambiguity limited non-ambiguous coverage to a narrow sector near the northern tip of Newfoundland and in the Gulf of St. Lawrence. A re-designed array configuration later permitted non-ambiguous reception over the entire illuminated area.

1.3 SARA OPERATING TECHNIQUES

The SARA system [5] has the unique capability of separately recording the signal received by each element in the antenna array, using phase-locked quadrature detectors in each receiver to

preserve both phase and amplitude information for later construction of antenna beams during analysis. In this way, the system can simultaneously observe all azimuths that are illuminated by the transmitter.

1.3.1 Range Selection and Analysis

The system uses frequency-modulated continuous-wave (FMCW) signals to permit discrimination in range. The precisely-controlled swept-frequency signals, after reflection from a target, return to the receiver with the usual delay. As illustrated in Fig. 2, comparison of the received signal against a locally-generated replica of the transmitted signal converts the time delay to a frequency offset. Targets at different ranges appear at different output frequencies, which makes the extent of the observable interval in range dependent upon the bandwidth of the receiver.

Discrimination in range is accomplished by the application of a complex Fourier transform to the output signal, which divides the range interval into a number of range cells, each represented by a spectral line. The content of each cell represents the complex summation of all targets, at that particular range, for all azimuths.

The bandwidth of the receiver, and thereby the number of range cells that can be observed simultaneously, is limited by the maximum sampling rate of the data-recording system. For the sea-state experiment, the parameters selected yielded a 72 km range interval, resolvable into 24 independent range cells. Each sweep of the signal waveform provided a fresh estimate of the contents of these 24 cells. For convenience in the analysis, the interval was divided into 32 not-quite-independent cells; later sections of this paper will refer to groups of 32 cells.

The position of the range interval, relative to the SARA site, is set at the time of recording, by delaying the start of the locally-generated replica of the sweep by an appropriate timing offset. The signals recorded represent the contents of an annulus or "range ring", about the radar, which has a radius set by the selected value of range offset and a range extent established by the receiver bandwidth. Of course, signals are observed only from that sector of the ring which intersects the area illuminated by the transmitter.

1.3.2 Beam Forming

Range-ring analysis is carried out for all of the signals recorded from all of the elements in the array. From those results, antenna beams are then synthesized by complex summation of the signals from corresponding range cells from each array element, after application of phase adjustments appropriate to the selected beam direction. This procedure is repeated for each of the 32 range cells, and, of course, is carried out for all of the frequency sweeps, each representing a fresh sample of information. The entire procedure must be repeated for each selected beam direction.

The beam direction is a line at an angle relative to the line of the array. When rotated about the array line, the beam direction describes the surface of a cone. For this reason, the selected beam directions are commonly referred to as "cone angles"; conversion of a cone angle to a bearing on the earth's surface requires an estimate of the elevation angle of the signal path. For this experiment, elevation angles were estimated externally by the use of vertical ionograms.

1.3.3 Measurement of Doppler Spectra

With reference to Fig. 2, it can be seen that Doppler offset of a returning signal is indistinguishable from an increment in range. The resulting error is made negligible by the appropriate choice of operating parameters. However, the Doppler spectrum contains the information needed for the experiment and so it must be extracted from the data.

Since the analysis procedures preserve both the phase and amplitude information of the signals representing the range cells, a complex Fourier transform applied to a sequence of samples from a particular range cell will produce a measure of the rate of change of range with time, which, in fact, is the Doppler spectrum. The repetition rate of the transmitted sweeps and the duration of the observation establish the Doppler bandwidth and the doppler resolution, respectively. The transformation is performed for all range cells and for all selected beam directions.

This final step in the routine analysis generates a Doppler spectrum for each ocean cell in the coverage area. These spectra are recorded on magnetic tape for the interpretive analysis to follow.

2.0 FACILITIES

2.1 RECEIVING SYSTEM

The SARA antenna array comprises 90 independent array elements, laid out in the shape of a cross, as illustrated in Fig. 3(a). The array used for an experiment may be tailored to the requirements of that experiment by the selection of any combination of these elements. Unused elements usually are removed. The number of elements used in an experiment is limited ultimately by the maximum sampling rate of the data-recording system, taking into consideration a number of interrelated factors such as resolution in range and Doppler, range window, Doppler bandwidth, acceptable levels of aliasing in range, and the available selection of sweep rates and receiver output filters. For the sea-state measurements, the parameters chosen dictated an array size of 42 elements.

Two 42-element configurations were tried. At first, in an attempt to obtain the minimum possible beamwidth (less than 1 degree), a sparse selection of elements was made along the full extent of the array, as illustrated in Fig. 3(b). The 32 closely-spaced central elements were combined in

pairs, reducing their number to 16 to allow all 26 of the outer elements to be used. Although this configuration was known to be ambiguous, it was thought that the ambiguities could be resolved or ignored, as had been possible in direction-finding experiments. To a large extent, this was not the case, however, and so the array had to be reconfigured. Some results were rescued from this early attempt by deleting the signals from the outer elements during the analysis procedures, producing a wider beam pattern with a capability for non-ambiguous reception from a small sector in the middle of the intended coverage area.

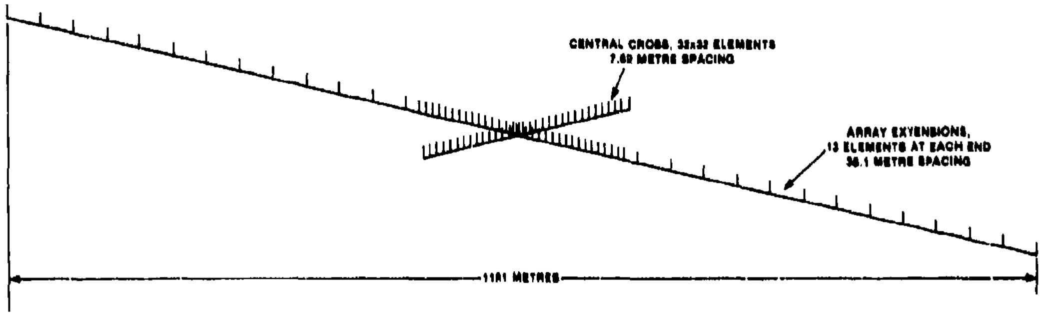

FIG. 3(a) The Complete SARA Antenna Array

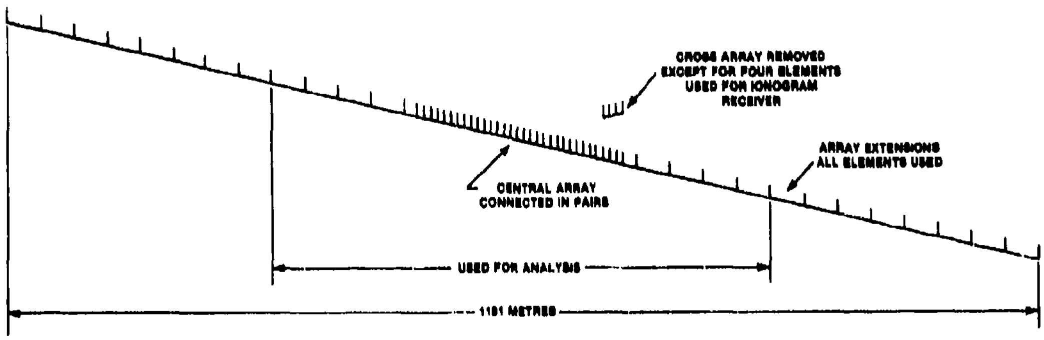

FIG. 3(b) Initial Array Used for Sea-State Experiments

Although signals were received from the entire array, ambiguity problems required that only the central portion of the array be used for analysis.

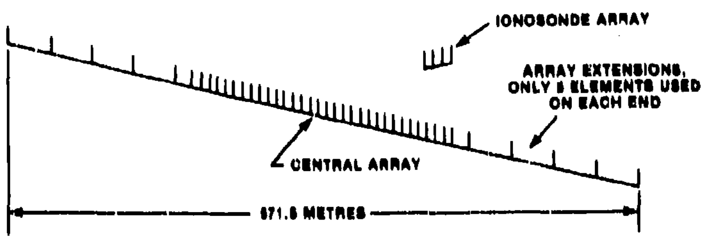

FIG. 3(c) Final Array Configuration Used for Sea-State Experiments

The elements of the closely-spaced centre portion were used individually for the final configuration.

The design of the second configuration, illustrated in Fig. 3(c), took these problems into account and accepted the wider beamwidth of a shorter array to avoid ambiguous responses within the coverage area. To reduce sidelobe responses, the design of the array necessarily included the application of an antenna-shading "window" function. In this case a cosine-squared window, applied as a function of distance along the array, suppressed sidelobe responses to a level about 20 decibels below the response of the main lobe. The beamwidth of the shortened array, with the "window" applied, was about 2 degrees.

For analysis of the limited coverage sector of the original configuration, the same window function was applied to the same array extent that was used in the second configuration, and the responses of the outlying elements were set to zero. This produced a beam pattern nearly identical to that of the second configuration, except for the ambiguous responses that emerged when the beam was steered outside the limited coverage area.

The SARA receiving and data-recording system is illustrated in Fig. 4. Important features of the system are:

(i) the antenna selection panel, where the selected array elements are interconnected with the bank of receivers;

(ii) the computer-controlled local-oscillator and frequency-sweep generator, which perform the functions of timing the receivers and de-ramping the swept-frequency signals by providing phase-matched local-oscillator and reference signals to all receivers;

(iii) the sample-and-hold unit which freezes the values of all of the receiver output signals when triggered by a sampling pulse from the timer;

(iv) the multiplexer, which sequentially scans the voltages held by the sample-and-hold unit, following each sampling pulse;

(v) the analogue-to-digital converter, which converts the signals to 12-bit digital representation;

(vi) the computer, which manages the task by controlling timing, event sequence and frequency selection, and formats the data into records for transmission to the tape recorder;

(vii) the frequency standard, to which all frequency-generation and timing functions are synchronized.

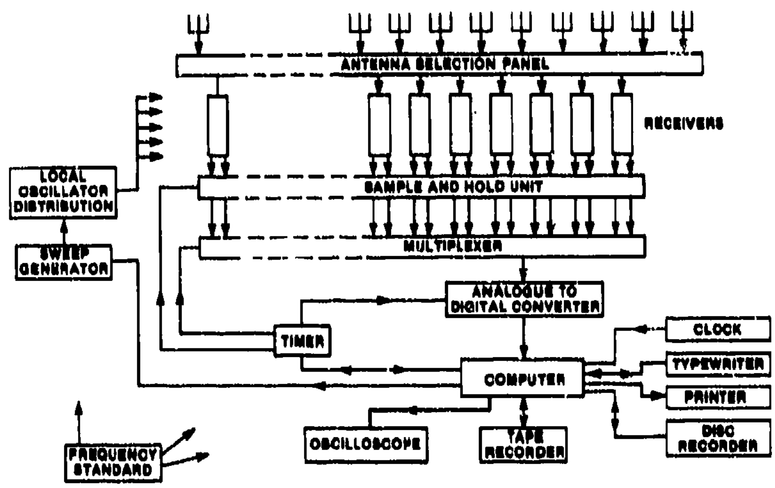

FIG. 4. <u>The SARA Receiving and Data-Recording System</u>

The required high precision of signal frequency selection and timing control is established by the rubidium frequency standard.

The receivers are locally-designed double-superheterodyne units, tuned across the 2-30 MHz band by computer selection of local-oscillator frequencies. Each receiver contains a quadrature detector which performs a third frequency translation to shift the output centre frequency to zero, with "positive" and "negative" frequency bands resolvable from the quadrature signals. The output bandwidth of each receiver, established by interchangeable post-detection low-pass filters, is quite narrow. For the sea-state experiment, the bandwidth used was $\pm$60-Hz. Each receiver has an independent automatic-gain-control (AGC) circuit. To enable restoration of the input signal voltages during analysis, the individual AGC control voltages were also sampled and recorded.

The signals from each receiver had to be sampled at a rate high enough to avoid significant aliasing ("Nyquist folding"). For the sea-state experiment the two output signals and the AGC voltage from each of the 42 receivers had to be sampled at a rate commensurate with the 60-Hz filters. This worked out to a total sampling rate of 25200 samples per second. This was easily handled by the analogue-to-digital converter, which can operate at rates up to 45000 samples per second, but approached the limiting rate of the tape recorder, which can accept up to about 27000 data words per second.

Ionograms were received by the same system, using a separate receiver and a separate antenna. The output bandwidth of the ionogram receiver is wide, to permit observation of the entire range of interest. Ionograms were analyzed on-line, for immediate presentation, and were also recorded to permit later re-analysis if necessary.

The Honeywell DDP516 computer system was also used for analysis tasks, both on-line and off-line. It is quite fast, despite its age, and is limited in capability only by the relatively small capacities of its memory and disc recorder, and by the availability of only one tape recorder. The computing facilities include a dot-addressable dot-matrix printer which, in concert with a full range of graphics software, can generate a variety of graphic print-outs, including Doppler spectra and gray-scale ionograms, all at high speeds.

2.2 TRANSMITTER

The target area in the ocean was illuminated by signals transmitted from the RADC transmitter facility at Ava, New York. That facility has available both a selection of transmitters and a selection of antennas. RADC is licensed for the transmission of low-power continuous sweeps across the entire band, and for high-power narrow-band sweeps within a series of 200-KHz bands distributed at approximately 2-MHz intervals across the band. The low-power continuous sweep mode is used for the generation of ionograms, the high-power mode for radar operations.

The sea-state experiment used a rotatable horizontally-polarized log-periodic antenna which had an azimuthal beamwidth of about 65° over its operating range of 6.5 to 30 MHz. This antenna was mounted on a 35-metre tower, which resulted in some unavoidable areas of poor illumination because of nulls in the elevation pattern. Power levels were limited to 5-10 KW for ionograms; 10-15 KW for radar. Although more radar power would have improved the signal-to-noise ratio in some cases, this was not possible because high power caused flash-over and damage to the antenna at the higher frequencies.

2.3 TRANSPONDER

A transponder, built by Stanford Research International, was installed at St. John's, Newfoundland, to provide a calibration point in bearing and range. The unit was operated continuously on all observing days, retransmitting all received signals with 8.5-Hz, suppressed-carrier amplitude modulation to generate a false-range, false-Doppler signature in the Doppler spectra whenever the analysis procedures selected the range cell surrounding St. John's. A directional array of Beverage elements was used as the antenna to provide a large cross-sectional area in the direction of Ottawa.

3.0 ANALYSIS TECHNIQUES

Analysis of the data recorded in the experiment was separated into four tasks:

(i) Analysis and presentation of ionograms, from which operating points were selected and virtual heights were derived;

(ii) Conversion of the recorded narrow-band "chirp" radar signals to a data-base of calibrated range rings;

(iii) Beam-forming and doppler analysis of the range-ring data to define Doppler spectra from indivi individual range cells; and

(iv) Interpretation of Doppler spectra to derive sea conditions.

The first two of these tasks were carried out entirely at CRC/SARA; the latter two were undertaken independently by both CRC and C-CORE. CRC effort was concentrated upon techniques of measuring wave-height; C-CORE effort upon techniques of automatic generation of wind-field maps by measurement of wave direction.

3.1 Analysis and Presentation of Ionograms

Ionograms were analysed and presented in real time by the SARA control computer. Although not equipped with a hardware fast-Fourier processor, the Honeywell computer is fast enough to convert incoming swept-frequency signals to ionograms in real time. Fig. 5 is a reproduction of a gray-scale backscatter ionogram which was drawn originally on a plain paper sheet approximately 28 X 50 cm, using the dot-addressable matrix printer attached to the computer.

A new ionogram was generated every 15 minutes, followed each time by the recording of two radar runs at two ranges selected from the ensemble that covered the area of interest. Both the ionogram signals and the radar signals were retained on tape.

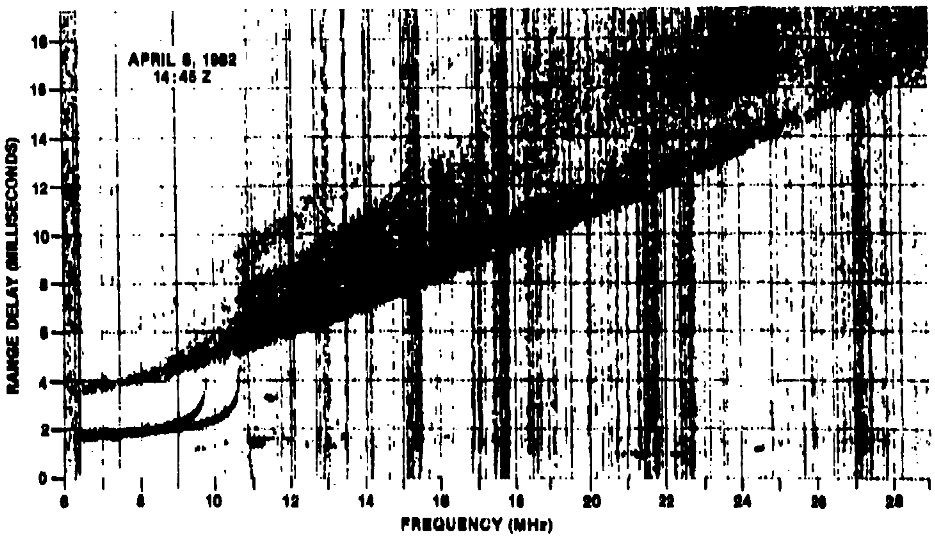

FIG. 5. Backscatter Ionogram

These were generated every fifteen minutes during experimental runs. The SARA control computer performed the required Fourier analysis and conversion to a graphic print-out in real time.

A portion of an overhead, nearly-vertical ionogram appeared in the lower left corner of each backscatter ionogram, resulting from illumination of the overhead ionosphere by sidelobe radiation from the transmitting antenna. Only the upper end of the overhead trace was available because of the 6.5 MHz lower operating limit of the transmitting antenna, but this was usually enough to determine the virtual height of the overhead ionosphere at the selected operating point, taking into consideration the usual transformation for angle of incidence. As is often the case in sea-state experiments, the ionosphere above the receiver was assumed to be a valid indicator of ionospheric conditions at the actual radar reflection point about 1000 Km away.

The backscatter trace, extending outwards from the double-hop overhead trace, was used for selection of the operating point. A technique for the optimum selection of signal frequency, based on the use of a nomogram overlay in conjunction with a complete overhead ionogram, has been described by U.S. workers [6]. Although the required vertical ionogram could have been generated by the use of CRC/SARA transmitting equipment, use of that technique would have provided little actual benefit, because of the very limited list of available operating frequencies. For this reason, operating points were chosen simply by selecting the highest available operating frequency that placed the range of interest behind the leading edge of the backscatter trace.

3.2 Generation of the Range-Ring Data Base

Conversion of the recorded signals to a set of calibrated range rings was the routine, although time-consuming, task of Fourier transformation of all of the de-ramped narrow-band sweeps from all of the receivers. This process converted the 512 individual "chirp" sweeps, recorded during each 102.4 second observation dwell, to 512 time samples for each of the 32 range cells. The resulting range-ring data file for each radar observation comprised 512 complex samples of 32 range cells for each of the 42 antenna elements.

The recording rate was high enough to permit a substantial "guard band" [7] for protection against Nyquist folding; signals aliased from outside the accepted range interval were suppressed more than 25 decibels. The data base was compiled at the CRC computing centre at a rate of about 6 to 8 data tapes per week, requiring a period of several weeks to process the recordings from one observing day.

3.3 BEAM-FORMING AND DOPPLER ANALYSIS, CRC

At CRC, the task of beam-forming and Doppler analysis was performed separately from interpretation in order that procedures requiring large storage arrays could be carried out at the CRC computing centre, while procedures involving spectral selection and alignment could be handled on-line at the SARA computer console.

3.3.1 Beam-Forming

Antenna beams were formed by the complex summation of signals sampled at the various elements along the array, after appropriate adjustments in phase. Use of this technique, rather than the equivalent but more efficient technique of Fourier transformation, was required because the elements in the array were not uniformly spaced. An advantage of the complex-arithmetic technique was the capability for arbitrary selection of azimuthal directions, independent of the array direction or the radio frequency.

Beams were formed for a fixed array of directions, at two-degree intervals, from a bearing of 51 degrees, which is part way up the Labrador coast, to 81 degrees, which is south of Newfoundland. The southern limit was sometimes extended to a bearing of 93 degrees, which was the limit of the illuminated area.

3.3.2 Doppler Analysis

Using fast-Fourier techniques, Doppler spectra were derived for each range cell in each selected beam direction, and for each observation interval.

Although the length of the observation interval had been set at 102.4 seconds at recording time, it was known that there would be problems of interpretation of a non-stationary process because individual ionospheric paths frequently exist for only a few seconds at a time, particularly at high magnetic latitudes [8]. Fourier analysis implicitly assumes a statistically stationary signal, but a long observation of a sky-wave signal may encompass the sum total of several propagation conditions which have appeared and disappeared at different times during the interval. In the final result, these appear as multipath components. To analyse the recorded data, a compromise had to be struck between a relatively long averaging time, which provided fine resolution in the Doppler spectra, and degradation of the spectra resulting from the non-stationary process. All of the CRC analysis has been carried out on half-intervals of the recorded data, i.e., each 102.4-second recorded interval has been treated as two contiguous 51.2-second intervals.

To suppress spectral leakage, with a minimum of line broadening, a Blackman-Harris minimum three-term window [9] was applied to each of the half-interval segments of the data. This brought about the required improvement but resulted in the suppression and effective loss of a considerable amount of data at the ends and in the middle of the observation interval. By re-analysis of the half-interval between the one-quarter and three-quarters points of the interval, and application of the same window, a third time interval was defined, permitting the recovery of much of the lost data and the generation of a third spectrum.

The three spectra, representing time intervals which overlapped 50%, actually were only 10% correlated because of the effect of the window function. Hence each range cell was represented by three nearly-independent Doppler spectra, producing a total of 96 spectra for the 32 range cells in each azimuthal direction, for each observation interval. These were recorded on a tape readable by the SARA control computer.

3.4 INTERPRETATION OF DOPPLER SPECTRA, CRC

The Doppler spectrum of a radar signal reflected from ocean waves is characterised by two "Bragg" peaks: strong spectral lines resulting from focussing of the reflected energy by the regular pattern of the waves, in a mechanism analogous to a diffraction grating. These peaks are superimposed upon a pedestal of second-order reflections which form a continuum of returns across a spectral width of about 2 Hz. In theory, several measures of sea conditions can be derived from this Doppler signature. These include wave height, wave direction, wind speed, sea-wave spectrum, dominant wave period, and velocity of ocean currents [10]. Since all of these are related to some aspect of the Doppler signature, the accuracy of measurements made by a sky-wave radar is degraded by the variable Doppler offset and Doppler smear imposed upon the signal returns by motion of the ionosphere. In particular, from signals reflected by the ionospheric F layer, only two sea conditions may be observable with a useful degree of confidence: wave height, derived from the ratio of the power of the prominent Bragg line to the power of the surrounding continuum; and wave (wind) direction, derived from the ratio of the power of the "approaching" Bragg line to that of the "receding" Bragg line.

A great deal of subjective analysis is necessary. To begin with, the reflection process at the sea surface displays considerable variance, necessitating the incoherent averaging of many individual spectra derived from several independent, closely-spaced time samples from several independent, closely-spaced range cells. In the absence of ionospheric effects, simple averaging of groups of up to 100 spectra usually can resolve all of the sea conditions listed above. However, the ionospheric Doppler anomalies imposed upon sky-wave radar returns, if unconditionally averaged over a large number of spectra, tend to degrade the final result to a smeared signature from which little or nothing can be derived. Ionospheric Doppler offset and the incidence of multipath propagation both vary considerably as functions of time and space. Their effects can be minimised by adjustments of the unconditionally-averaged spectra prior to final averaging: spectra displaying significant multipath effects can be discarded; those showing Doppler offsets can be shifted to align the Bragg lines of the sea-echo spectra. Several observations of the same cell are frequently necessary to obtain a useful result.

The high variance of the reflection and propagation processes imposed a dilemma: the averaged results were needed to accurately assess the ionospheric effects, but those effects had to be minimised to obtain the average. The working compromise employed unconditional averaging of subsets of the ensemble of individual spectra, to produce a set of spectra useful for estimating ionospheric

effects, followed by selection, alignment and conditioning of the unconditional averages prior to the calculation of the final average from which sea-state characteristics were derived.

At CRC the 96 spectra from an observation interval were first unconditionally averaged in groups of 12: three "overlapped" spectra from each of four contiguous range cells. This produced eight unconditionally-averaged spectra from each observation interval. These were examined individually by the experimenter on the console oscilloscope of the SARA computer, assisted by a controllable flashing display which indicated the expected separation of the Bragg lines. Each of the eight spectra was either rejected or tagged to indicate the experimenter's best estimate of the location of the dominant Bragg line. The final average spectrum, assumed to represent conditions for the entire 32-cell range interval, was derived from the accepted spectra after alignment of the Bragg lines according to the experimenter's tags, and normalization in amplitude in accordance with the geometric mean of the power in the dominant Bragg lines. The process is illustrated in Figs. 6(a), 6(b) and 6(c).

Some post-averaging selection was also done; in particular if fewer than three unconditional averages were included in the final average the measurement of wave height was not considered valid.

Before this manual technique was adopted, considerable effort was expended upon attempts to mechanise the selection/alignment process but this met with very little success. The definition of an acceptable spectrum was difficult because of the wide range of acceptable spectral shapes, and automatic methods of determining the position of the dominant Bragg line frequently selected incorrect peaks. The technique of rejecting spectra on the basis of the "equivalent width" of the dominant Bragg line, used by the U.S. workers [11] in their automated scheme, tended to reject all of the spectra recorded by this experiment. Although the manual technique is cumbersome and time-consuming, it has managed to extract useful results from relatively poor data and is providing both statistics and experience which may lead to the design of an automatic procedure.

Wave heights reported in this paper are those defined as "significant wave heights", i.e. r.m.s. wave heights multiplied by four. They were estimated by use of the Maresca-Georges power-law relation [12]

$$h = \frac{aR^b}{k_o}, \quad hk_o > 0.2$$

where h = r.m.s. wave height,

R = unweighted ratio of second-order to first-order power encompassing the dominant Bragg line,

k_o = radar wavenumber,

a,b = constants, 0.8 and 0.6, respectively, found by Maresca and Georges to be the best overall power-law fit to their data.

Use of this technique implies a knowledge of the location of the nulls which separate the Bragg line from the second-order continuum, but since those nulls are rarely observed in sky-wave data (never in the Canadian data) they were assumed to lie at 0.07 Hz [13] each side of the peak of the Bragg line.

Wave directions were estimated from the ratio of the power in the two Bragg lines by use of the Long-Trizna [14] formula:

$$\rho = 20 \log \left(\frac{0.56 + 0.5 \cos 2\theta}{\pi} \right) + 34.02 \text{ decibels}$$

where ρ = Bragg line power ratio

θ = angle between the radio-wave propagation direction and the mean sea-wave direction.

3.5 AUTOMATIC ANALYSIS TECHNIQUES, C-CORE

At C-CORE, analysis effort was directed towards the development of automatic methods for the extraction of wind (wave) direction. The analysis system derives wind directions for a specific set of geographical locations, for comparison against hindcast maps of wind directions obtained from meteorological data.

Initially, attempts were made to devise an automatic scheme to measure both wave height and wave direction but, for the data available, it was found that the algorithms could not consistently identify the spectral characteristics required for the measurement of wave height. Nearly all of the wave height results had to be rejected. However, for the measurement of wave direction, sufficient success was achieved to warrant continued analysis.

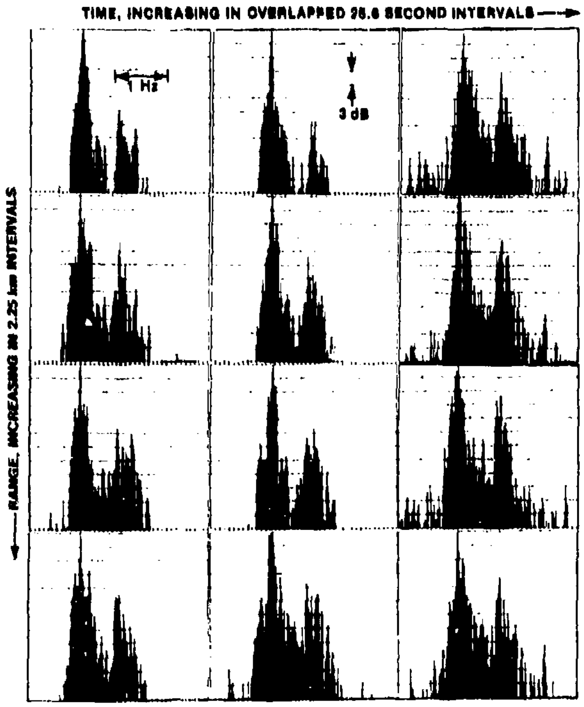

FIG. 6(a) A Set of 12 Spectra Representing 4 Contiguous Range Cells for 3 Overlapping Observation Intervals

Each subgroup of twelve spectra was averaged, without adjustment, to generate an unconditional average representing one group of four range cells for the entire observation interval.

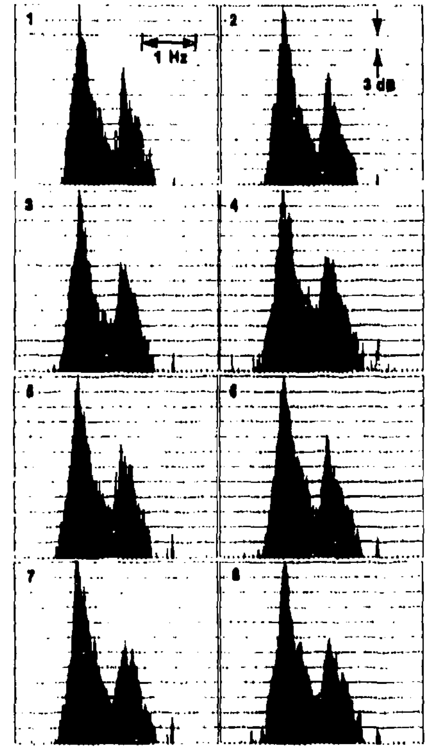

FIG. 6(b) Eight Unconditionally-Averaged Spectra Representing Eight Groups of Four Range Cells Each

Each of these spectra is the result of the unconditional averaging of a group of twelve individual spectra. The group shown in Fig. 6(a) produced spectrum number 3. Spectra 1, 2, 3 and 6 from this set were accepted for alignment, normalization and final averaging.

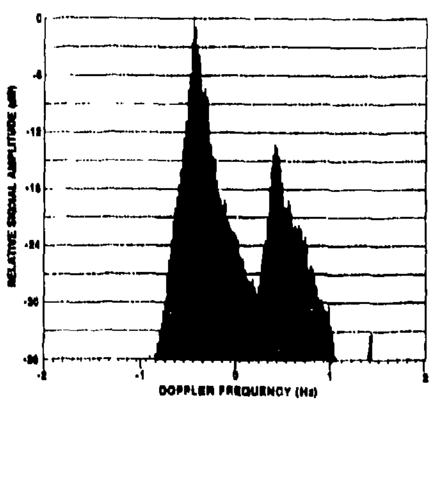

FIG. 6(c) Re-Aligned, Normalized Final Average Spectrum

The final spectrum resulting from the processing of the four selected spectra from Fig. 6(b) has been centred for presentation. Analysis of its characteristics yielded a wave direction of 23.4 degrees and a wave height of 3.3 metres, both of which agreed closely with hindcast surface data.

The analysis procedure divided the 102.4-second observation interval, represented by 512 complex samples from each receiver, into seven sub-intervals of 128 complex samples each. The sub-intervals were 50% overlapped. Each sub-interval was transformed to a spectrum after application of a Blackman-Harris window function. The seven spectra from each range cell were unconditionally averaged; then the averaged spectra from each of eight contiguous range cells were aligned and averaged to create one final spectrum representing one-quarter of the 72 Km range interval. Using the Long-Trizna formula, a wind direction was calculated from the ratio of the two Bragg peaks. The spectra, and the resulting wind maps, were automatically plotted for examination and post-analysis acceptance.

Attempts made to introduce a quality-control index have been unsuccessful. An index based upon the normalized ratio of adjacent peaks and troughs within the spectrum has been developed as a possible indicator of ionospheric contamination, but it remains to be seen whether it can be used as a satisfactory post-analysis acceptance criterion. It is more tolerant than the Georges-Maresca "equivalent width" [11] technique, which rejects virtually all of the Canadian data. Because of the lack of an acceptable mechanism for rejection of poor results, quality control has been carried out by visual inspection of the plotted spectra, after analysis. Wind directions were retained only for accepted spectra.

Automatic methods of alignment of the unconditionally averaged spectra, as a means of reducing ionospheric effects, still pose problems. Attempts were made to align spectra by determination of the position of the dominant Bragg peak, taking into account the content of the target cell (land, coast-line or ocean), but gross misalignments tended to occur if noisy spectra were intermixed with good spectra or if adjacent spectra represented different types of targets.

The alignment technique employed made use of measures of the average value and the centroid of each spectrum to estimate the required shift in frequency. Beginning at the centroid, the algorithm searched outwards, in each direction, until it found a point where the power dropped below the average value. The midpoint between the limits thus found was assumed to be the correct midpoint of the spectrum for purposes of alignment. The advantage of the use of this method was its relative insensitivity to the effects of target types and mixtures of target types, e.g., along a coastline one cell could be on land and the next on the ocean. The technique caused a certain amount of smearing of the Bragg lines, but appeared to be suited to the alignment of the short (128 point) intervals used in the analyses.

CRC results indicate that satisfactory wind directions frequently can be derived from unconditional spectral averages; this suggests that a simplification of the C-CORE techniques might be possible.

4.0 RESULTS, CRC

CRC analysis effort was focussed upon the derivation of wave height. Of course, any spectrum that yielded an acceptable measure of wave height also yielded a wave direction. In fact, it was possible to make measurements of wave direction even in the presence of severe multipath distortion because the analysis technique permitted the experimenter to stipulate which spectral lines were the Bragg peaks. As a result, the CRC analysis procedures produced complete wave-direction maps as a by-product of the wave-height analysis. On the other hand, the wave-height maps displayed only a sparse distribution of results because of the difficulty of obtaining sufficient numbers of acceptable unconditionally-averaged spectra to generate a useful final spectrum.

Two observing days were analyzed: April 9, 1981, when waves were generally about two metres in height; and April 8, 1982, when an Atlantic storm south of Newfoundland produced wave heights of 4 to 7 metres within the radar coverage area.

It should be noted that the success to be described in the analysis of these two selected runs was not generally attainable. Preliminary analysis of other runs indicated that many of them will produce little or no results.

4.1 April 9, 1981

Wave heights measured on April 9, 1981, are shown in Fig. 7, overlaid on conventional hindcast wave height contours derived from meteorological data and ship reports. The radar results were obtained using the ambiguous array configuration, and so the southern half of the plotted data may have been influenced by signals received from an area near the northern edge of the map. The northern half of the plotted data is free from ambiguous returns.

The measured wave heights were somewhat high, varying from correct values to about double the correct values. Bias toward high readings is to be expected if power from the focussed Bragg lines is shifted into the second-order continuum by the effects of ionospheric multipath propagation. This is particularly important when wave heights are low, because the signal power returned in the second-order continuum is then relatively low, making the ratio of Bragg line power to continuum power very sensitive to contamination.

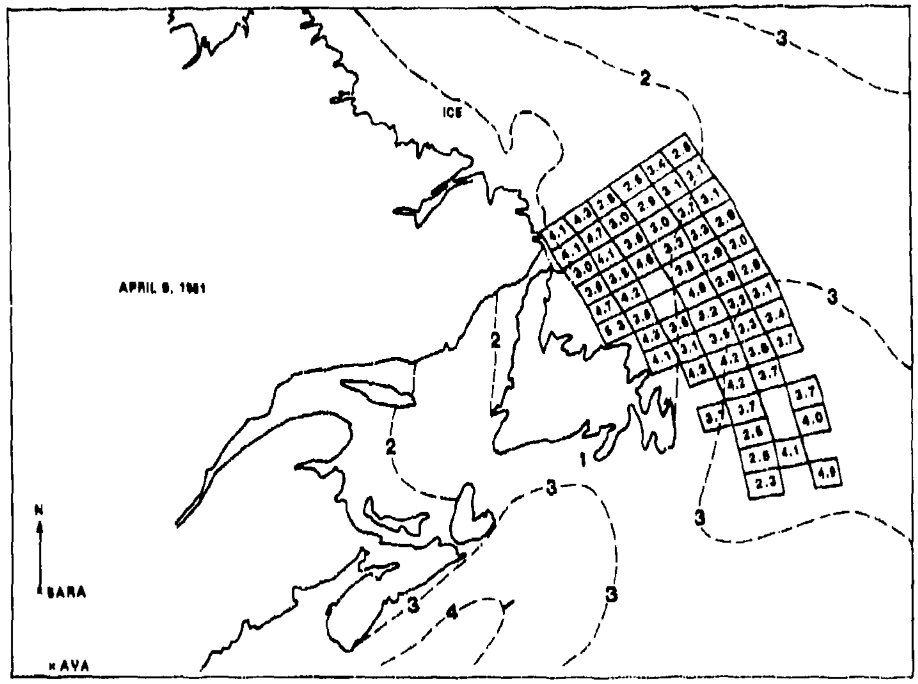

FIG. 7. Wave Heights Measured on April 9, 1981

The contours are hindcast wave height maps from meteorological data. The radar data appears to be biased towards higher readings.

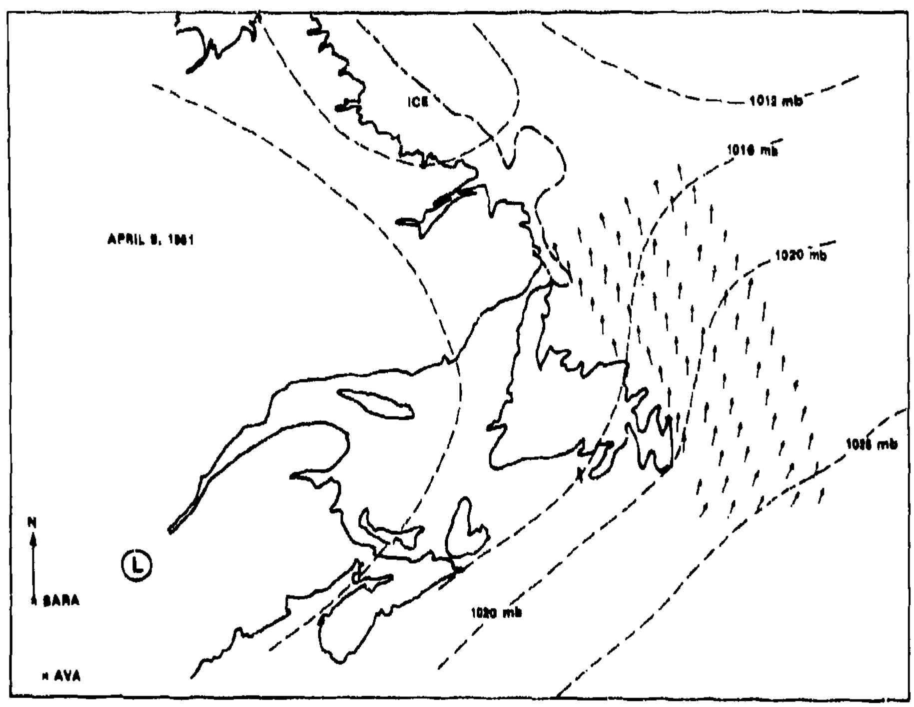

FIG. 8. Wave Directions Measured on April 9, 1981

The radar measurements are both self-consistent and consistent with the meteorological isobars.

The corresponding wave-direction map is shown in Fig. 8, overlaid on hindcast pressure isobars. Self-consistency of the results is clear, as is consistency with the air pressure contours. Wave direction maps produced by a single radar necessarily display a right/left ambiguity, but since this was resolved by the weather map it was not shown here.

Three observation passes were made over the coverage area. Only the results from the second pass are illustrated in Fig. 8. The third pass produced similar results; the first pass was too poor to be of use. Returns from the Gulf of St. Lawrence were not analyzed.

4.2 April 8, 1982

Four passes were made over the coverage area during the six hours of observation on April 8, 1982. Use of the re-designed array configuration provided coverage of the entire area without ambiguous responses.

The wave height results were sparse. All of the acceptable results, from all four observation passes, are shown in Fig. 9, overlaid on a hindcast wave-height contour map. The radar returns were recorded over the period 14:00Z to 20:00Z; the contour map was compiled effective 12:00Z. The Atlantic storm, with 11 metre waves at its centre, was approaching from the south. The radar measurements agreed quite well with the hindcast map. There was only one conspicuously high value. The wave heights shown within the land area of northern Newfoundland, which are thought to be the result of sidelobe responses, were in agreement with the low wave heights near the tip of the island.

The corresponding wave-direction map, Fig. 10, shows good agreement with expected wind directions. The pressure isobars were plotted for an effective time of 18:00Z. As was the case for wave heights, wave directions apparently measured over land areas agreed with wind directions expected over nearby ocean areas. The wave direction measurements produced more than one result for most measurement cells, but since these all showed general agreement, only one was plotted for each cell.

Assessment of radar errors, by comparison of radar results against meteorological data and ship reports, is made difficult by uncertainty in the surface data and by difference in the time of observation. For example, some of the wave height results plotted in Fig. 9 were recorded more than 6 hours after the effective time of the hindcast wave height contours. When that data was extracted and compared against the more timely hindcast map compiled for 24:00Z, it was found that the agreement was poor at the southern limit of the area. The surface data indicated that the approaching storm had entered the area, while the radar data indicated that it had not. Some qualification is necessary whenever comparisons are made.

5.0 RESULTS, C-CORE

The map shown in Fig. 11 is a composite of accepted wave directions from selected areas of open ocean observed on March 26, 1982. Extensive ice cover along the coastline reduced the number of observation cells to 81, from which 47 yielded wave directions. The inherent right/left ambiguity of the radar results was resolved by comparison to meteorological data. Only one wave direction was plotted for each cell, although up to three results were obtained from analysis of the three radar passes over the area. In all but three cells the results were consistent.

The difference in wave direction displayed by the two southernmost observation areas was consistent with an area of high atmospheric pressure located just off the southeastern corner of the map.

This map was produced from what is thought to be one of the best observing days. Even so, more than three-quarters of the spectra produced were considered to be unacceptable. From the 327 spectra obtained from the 82 target cells, only 79 were accepted. Most of the rejected spectra displayed either significant ionospheric contamination or inadequate signal strength. In some cases it was obvious that the spectra had not been correctly aligned and consequently the Bragg peak had not been correctly identified.

Some of the analysis problems are illustrated by the unrelated spectra shown in Fig. 12. Although spectra A and B are quite similar, both displaying readily identifiable Bragg peaks, spectrum B was misaligned by failure of the centering algorithm, which incorrectly identified the right-hand limit at the point indicated by the arrow. Spectra C and D both displayed multipath contamination and so were rejected after visual inspection.

It was realised that inclusion of all initial spectra into the averaging process would result in a high rejection rate of the final averages, but it was felt that the use of a short observation time and the inclusion of only a small number of range cells would usually provide an acceptable final average spectrum. However, it appears that the rejection rate may be still too high to build adequate wind direction maps from the available data.

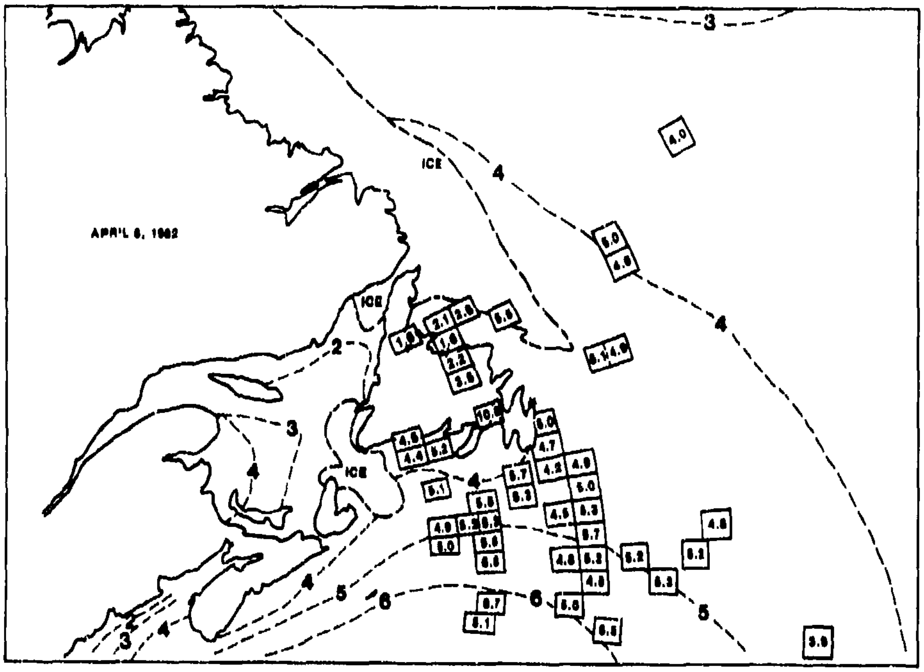

FIG. 9. Wave Heights Measured on April 8, 1982

At higher wave heights, the radar results agree more closely with the meteorological data. The radar data was recorded between 14:00Z and 20:00Z; the hindcast wave height contours were plotted effective 12:00Z.

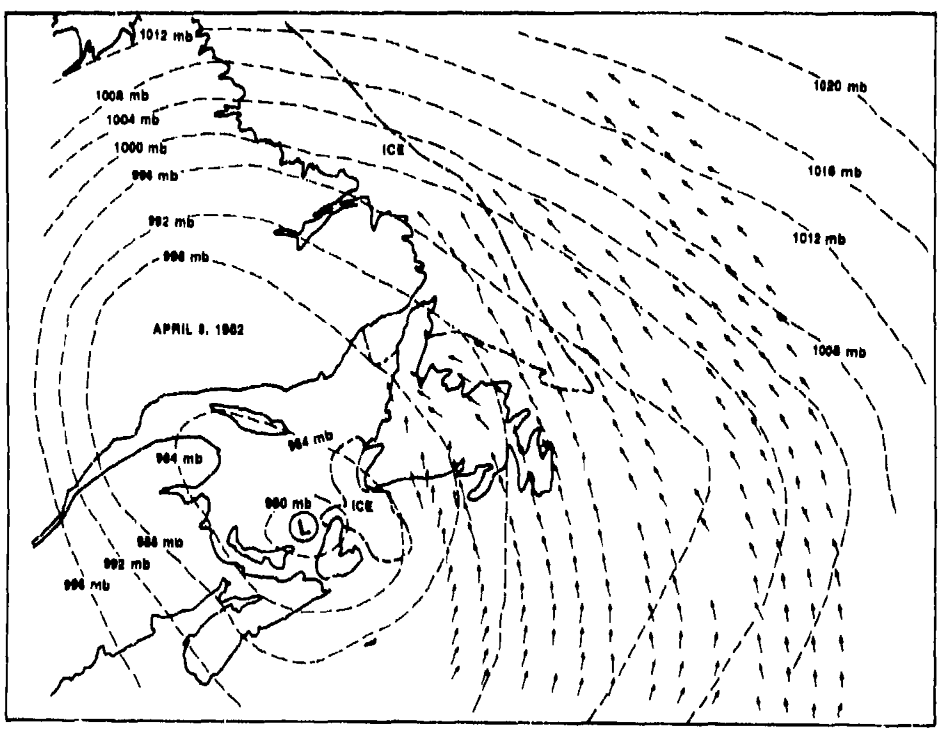

FIG. 10. Wave Directions Measured on April 8, 1982

The radar data were recorded between 14:00Z and 20:00Z; the hindcast meteorological isobars were plotted effective 18:00Z.

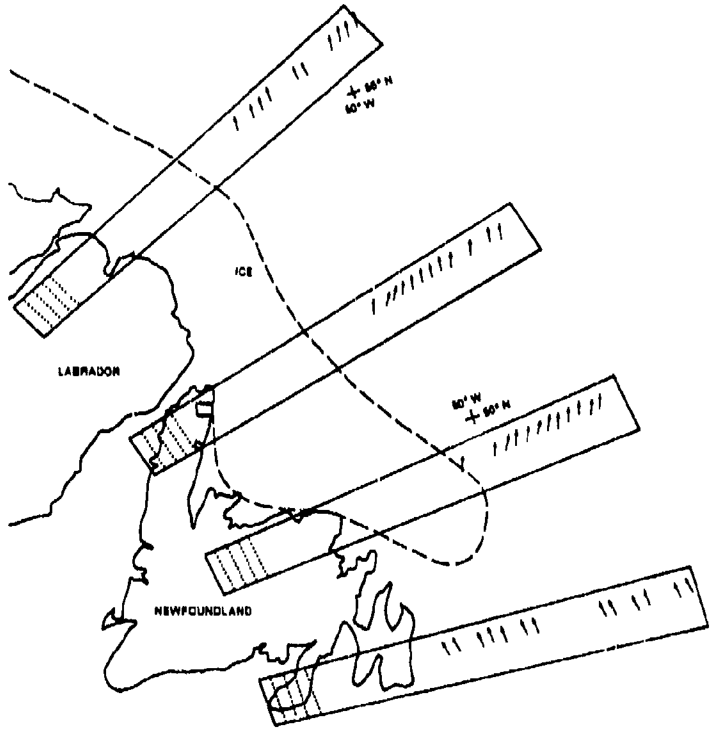

FIG. 11. Composite Wave Direction Map, March 26, 1982

The arrows indicate the wave directions for results retained after visual inspection of the spectra. Each arrow indicates the one result obtained from the averaging of the spectra from 8 adjacent range cells. The size of the final target cell is indicated by the dotted areas shown on the western end of the sample areas.

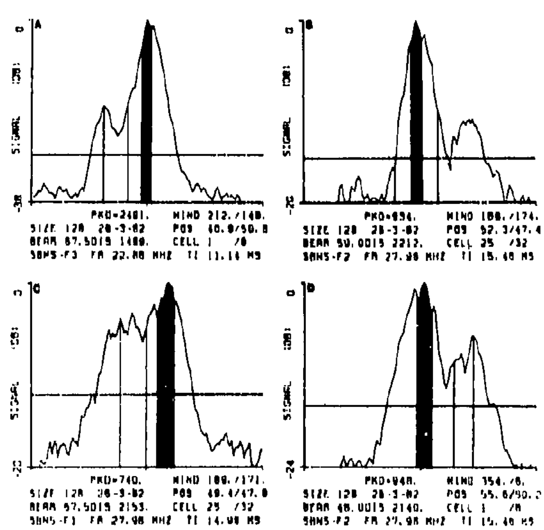

FIG. 12. Samples of Spectra from Automatic Processing of One of the Better-Quality Data Sets, March 26, 1982

The vertical lines indicate the positions of the Bragg peaks and the centroid of the spectrum as identified by the algorithms. The horizontal line indicates the average value (power) of the spectrum. A proposed quality index is reported as "PKD", higher values indicating better quality.

From these examples, spectrum A was the only one accepted. Although spectrum B was similar in quality, the search strategy failed because of the low point indicated by the arrow.

6.0 CONCLUSIONS

At a skywave sea-state radar workshop held in Rockville, Maryland, in May, 1981 [15], required capabilities for operational skywave radars were proposed. Among these were:

(i) accuracy of measurement:

wave height: $\pm$0.5m or $\pm$10%

wave direction: $\pm$20 degrees

position fixes: $\pm$25 km

(ii) frequency of reports: twice daily.

From the limited amount of data so far analysed in this experiment, there is some basis for optimism that the accuracy requirements for wave height and wave direction may be met, even at the geomagnetic latitudes of the Canadian environment. Measurement of wave direction does not appear to be a problem; the manual technique derived valid results even from unconditional averages of the spectra, and an automatic analysis technique appears to be feasible. Accurate measurement of low wave heights (2 or 3 metres) has been found to be difficult because of the sensitivity of the process to multipath contamination.

The problem of accurate position fixes, under study but not reported here, may present some difficulties. Position fixes depend upon accuracy in the determination of both the beam direction and the virtual height of the ionosphere. Direction-finding experience with ionospheric tilts, and with remote estimates of virtual height, suggests that the $\pm$25 km specification may not be attainable for radar signals propagated via the F region.

The most formidable problem, however, is likely to be the requirement for twice-daily coverage. As indicated earlier, the results given here were selected because they were successful. Although the scope of this experiment was not sufficient to yield an estimate of reliability (even with more complete analysis), the problems of finding good operating days during the execution of the experiment indicate that there would be significant gaps in coverage by an operational radar. Night-time operations have not been examined at all. However, the U.S. workers, at the Wide Aperture Receiving Facility in California [16], have demonstrated a capability for more-or-less routine operation, at l ast at their geomagnetic latitudes. Their technique is dependent upon a capability for on-line real-time analysis, which permits the experimenter to persist until he succeeds, and upon freedom of choice of operating frequency.

It is hoped that continued effort to analyse the remainder of the data recorded in this experiment will shed more light on all of these questions.

7.0 ACKNOWLEDGEMENTS

CRC activities in this experiment were funded by the Department of National Defence; C-CORE activities by the Department of Fisheries and Oceans. Participation by Rome Air Development Center was part of an international memorandum of understanding that included other projects.

REFERENCES

1. W.A. Sandham, "Remote Sensing of Oceanic Winds Using HF Radar", Departmental Memorandum No. 475, Dept. of Electronic and Electrical Engineering, Univ. of Birmingham, Dec. 1979.

2. W.A. Sandham and S. Theodoridis, "HF Radar Observations of Surface Winds in the Rockall Area During the Jasin Experiment of 1978", Departmental Memorandum No. 476, Dept. of Electronic and Electrical Engineering, Univ. of Birmingham, April 1980.

3. W.A. Sandham, "Some Notes Regarding HF Sea-Echo Doppler Spectra Inversion Techniques", Departmental Memorandum No. 478, Dept. of Electronic and Electrical Engineering, Univ. of Birmingham, August 1980.

4. E.D.R. Shearman, "Remote Sensing of Sea-State and Surface Wind by HF Radar", Interim Report 1.4.78-31.3.80, Dept. of Electronic and Electrical Engineering, Univ. of Birmingham.

5. D.W. Rice and E.L. Winacott, "A Sampling Array for HF Direction-Finding Research", CRC Report No. 1310, Communications Research Centre, Dept. of Communications, Canada, Nov. 1977.

6. T.M. Georges, "Progress Toward a Practical Skywave Sea-State Radar", IEEE Trans. Antennas Propagation, Vol. AP-28, pp. 751-761, 1980.

7. D.W. Rice and E.L. Winacott, Nov. 1977, p. 31.

8. B.J. Rook, "Study of the Behaviour and Stability of Phase Fronts on Short Time Scales", CRC Report No. 1312, Communications Research Centre, Dept. of Communications, Canada, February 1978.

9. F.J. Harris, "On the Use of Windows for Harmonic Analysis With the Discrete Fourier Transform", Proc. IEEE, 66, pp. 51-83, 1978.

10. T.M. Georges, 1980, p. 752.

11. T.M. Georges and J.W. Maresca, Jr., "The Effects of Space and Time Resolution on the Quality of Sea-Echo Doppler Spectra Measured with HF Skywave Radar", Radio Sci., Vol. 14, pp. 455-469, 1979.

12. J.W. Maresca, Jr. and T.M. Georges, "Measuring rms Waveheight and the Scalar Ocean Wave Spectrum with HF Skywave Radar", J. Geophys. Res., Vol. 85, pp. 2759-2771, 1980.

13. T.M. Georges, J.W. Maresca, C.T. Carlson, J.P. Riley, R.M. Jones, D.E. Westover, "Recovering Ocean Waveheight from HF Radar Sea Echoes Distorted by Imperfect Ionospheric Reflection", NOAA Technical Memorandum ERL WPL-73, 1981, p. 63.

14. A.E. Long and D.B. Trizna, "Mapping of North Atlantic Winds by HF Radar Sea Backscatter Interpretation", IEEE Trans. Antennas Propagation, Vol. AP-21, pp. 680-685, 1973.

15. T.M. Georges, J.W. Maresca, Jr., "Report on the Skywave Sea-State-Radar Workshop Held in Rockville, Maryland, 20-22 May 1981", NOAA Technical Memorandum ERL WPL-81, 1981, pp. 15-16.

16. T.M. Georges, 1980, p. 760.